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Examining the Runoff Reduction Potential of Highway Swales

Bailee Young
University of Tennessee, byoung24@vols.utk.edu

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I am submitting herewith a thesis written by Bailee Young entitled "Examining the Runoff Reduction Potential of Highway Swales." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Jon M. Hathaway, Major Professor

We have read this thesis and recommend its acceptance:

Qiang He, John S. Schwartz

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Examining the Runoff Reduction Potential of Highway Swales

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ABSTRACT

Across the country, the impacts of stormwater runoff are being managed through the National Pollutant Discharge Elimination System intended to ensure the licensee makes advances toward more environmentally-sensitive management strategies. Departments of Transportation fall within this regulatory framework, being tasked with reducing the volume of runoff as well as pollutant concentrations leaving their catchments. Stormwater runoff along highways contains pollutants which may be detrimental to local surface waters. However, the highway environment also has substantial amounts of green space. There are questions as to how much runoff reduction and pollution abatement are provided by these spaces, as their function will have a dramatic impact on stormwater management strategies. A highway median swale, located on Asheville Highway, Knoxville, Tennessee, was monitored over an 11-month period. The total catchment was 1.58 acres, with 0.64 acres of roadway draining to 0.94 acres of vegetated median. Runoff volume, rainfall, and water quality data were monitored. The results of this study indicated that 87.2% of runoff volume was reduced by the swale. Conversely, water quality results were variable. While 91.0% of total suspended solids were reduced, the results for nutrients and chloride were variable. Chloride and phosphate were exported while ammonium and nitrite-nitrate were reduced. The swale was also found to export heavy metals: copper, lead, and zinc. The reason for this variable performance may be related to the low pollutant concentrations entering the swale, or the fact that the inlet flume only captured a portion of the runoff entering the system. This may have resulted in a poor representation of the inflows to the system. The Source Loading and Management Model for Windows (WinSLAMM) was used to model the swale's runoff reduction performance. To calibrate the model, adjustments were made to measured on-site infiltration rates. Adjusting the infiltration rates had considerable effects on the model's output, and the calibrated model was only 28.4% different from the measured runoff volume. WinSLAMM proved to be a beneficial resource to assess green space performance; however, future studies are needed to determine which model inputs affect performance the most, which can be estimated, and which require on-site measurements.

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CHAPTER ONE
LITERATURE REVIEW

Introduction

According to the most currently available Water Quality Assessment, 53% of assessed stream miles, 71% of assessed lake acres, and 80% of assessed bay and estuarine square miles in the United States were impaired and failed to meet water quality standards (USEPA 2017). Stormwater runoff has been recognized as one primary cause of pollution in surface waters, containing high concentrations of pollutants, such as pesticides, fertilizers, oils, salt, litter, debris, and sediment (USEPA 2000). These pollutants rest on impervious surfaces until a rain event occurs, washing them into the stormwater system (Burton and Pitt 2002). The pollutants are transferred to waterways at the outlet of the system which can cause fish kills, habitat destruction, poor aesthetics, drinking water impairment, and a threat to public health (USEPA 2000). Increases in imperviousness also lead to higher peak flow rates and total runoff volume from watersheds (Weiss et al. 2010), with detrimental effects to stream stability and ecology.

To control water pollution, the Clean Water Act was established in 1972. It was formed as a series of amendments to the Federal Water Pollution Control Act of 1948 which addressed water pollution for the first time through a major U.S. law (USEPA 2016a). The Clean Water Act set standards for each pollutant in surface waters, inhibited the discharge of point source pollutants into navigable waters without a permit, and aimed to handle nonpoint source pollution in the future. The Clean Water Act created a framework for pollutant discharge regulations and established the EPA's authority to set standards for pollution control. The USEPA developed a permit program, the National Pollutant Discharge Elimination System, to regulate point source pollutant release into U.S. waterways (USEPA 2016c). The Storm Water Program was established in 1990 to manage stormwater discharge from municipal separate storm sewer systems (MS4s), construction and industrial projects, and EPA designated problem areas (USEPA 2016c).

State highway systems are required to operate under these requirements since stormwater runoff pollutants are transferred along roads from neighboring land and from vehicles' tires, brakes, engine wear, and lubricating fluids (USEPA 2015). The USEPA regulates State DOT's as nontraditional MS4s (USEPA 2015), which requires the highway system to develop, apply, and enforce a program to reduce pollutant discharge (USEPA 2000). The Statewide Storm Water Management Plan (SSWMP) was developed by the Tennessee Department of Transportation (TDOT) and presented to the Tennessee Department of Environment and Conservation (TDEC) on May 10, 2007 (TDOT 2016). The goals of the plan included sediment control, erosion prevention, and storm water management throughout Tennessee focusing on the state's highways (TDOT 2016). The following six control measures are presented in the plan: 1) Public education and outreach, 2) Public involvement/participation, 3) Illicit discharge detection and elimination, 4) Construction site storm water runoff control, 5) Post-construction storm water management in new development and redevelopment, and 6) Pollution prevention/good housekeeping for TDOT operations (TDOT 2006).

Vegetated Swales

To achieve their post-construction stormwater goals, state transportation departments are increasingly in need of Stormwater Control Measures (SCM) that are both effective in reaching MS4 stormwater requirements, and applicable to the highway environment. One SCM, designed to help satisfy MS4 requirements by reducing pollutants, increasing infiltration, and decreasing the stormwater velocity is the vegetated (grassed) swale (USEPA 1999). Grass swales convey water while enhancing the hydrology and water quality characteristics of urban runoff. They have the potential to counteract existing hydrologic issues and support predevelopment hydrologic conditions (Davis et al. 2011). Specifically, highway swales are typically built to transfer runoff away from transportation infrastructure during the largest storm events; however, most storm events are smaller than the design storms, potentially providing the opportunity for substantial hydrologic and water quality improvements during the smaller, more frequent events

(Davis et al. 2011). Essentially, an opportunity may exist to identify large stormwater treatment benefits in existing highway green space.

Pollutants are removed by filtration from the grass blades, sedimentation, infiltration, and soil interactions (Winston et al. 2012). Swales can be added or used to replace certain parts of a storm water drainage system, especially for areas with smaller populations and low flow (USEPA 1999). The pollutants of foremost concern in stormwater are total suspended solids (TSS), phosphorus (P), nitrogen (N), cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn) (Weiss et al. 2010). According to the USEPA (1999), swales characteristically reduce particulate pollutants by 25 to 50 percent, while soluble pollutants are reduced by less than 10 percent. In Durham, NC, an artificial swale lowered particulate heavy metal concentrations of Cu, Pb, Zn, and Cd by 50 percent, but performed poorly for soluble nutrients (USEPA 1999). Particulate pollutants include sediment, some species of nutrients, metals, and the portion of bacteria bound to sediment. Swales produce the best results when they are combined with other low impact development (LID) practices (USEPA 1999). In swales, volume reduction occurs as stormwater is infiltrated into the soil. Infiltration occurs both laterally over the swale side slope and longitudinally along the swale pathway (Weiss et al. 2010). Sedimentation occurs as water travels over the side slope and down the length of the swale, allowing solid particles to fall onto the surface of the soil, vegetation in the swales then acts as a filtration device, trapping solid particles (Abida and Sabourin 2006). Dissolved pollutants are removed by infiltrating into the soil (Abida and Sabourin 2006).

Swale Characteristics

Swale Geometry

The contributing watershed's area, slope, and perviousness must be examined along with the geometry of the channel to determine the swale's effectiveness, along (USEPA 1999). According to the Tennessee Stormwater Management Manual (2015), vegetative swales should be constructed on grades below 5% with longitudinal slopes below 4% to reduce the flow's velocity. Ferguson (1988) determined that velocities through the swales should be less than 0.15 m/s with a residence time no shorter than 9 minutes since increased detention time leads to increased pollutant removal (Yu et al. 2001). Mazer et al. (2001) supports a more conservative value for longitudinal slope of 1.5%. Swales must be designed to enhance water quality for flows at or below design flow and must be able to release high flows from large storm events (USEPA 1999). The channel should be parabolic or trapezoidal to increase the wetted perimeter, and side slope steepness should be limited to a 1:3 slope to reduce flow velocity (USEPA 1999). Occasionally the grass in the swale's bottom will be submerged, but the grass in grass filter strips is typically non-submerged (CIRIA 2000).

Vegetation

Vegetation is one way to reduce flow velocity since it increases channel roughness (Deletic et al. 2001). Deletic (2001) found that the roughness of the grass provided time for infiltration to occur. The health and quantity of the vegetation is an important factor in swale performance (Weiss et al. 2010), and different vegetation types uptake different types of pollution and thus influence pollutant removal efficiencies (USEPA 1999). Vegetation reduces the amount of sediment, nutrients, and heavy metals in stormwater. Grass effectively contains sediment by lengthening the transit time of the sediment particles, allowing them to fall out of the flow of water (Deletic 2001). Mazer et al. (2001) found that aboveground stems, leaves, and stolons increased sedimentation. Plant roots were also found to stabilize sediment deposits which reduces the occurrence of re-suspension (Mazer et al. 2001). In addition to sediment removal from grass, the nutrients and heavy metals attached to the sediment are also removed (Deletic 2001). Since vegetation is a pivotal part of swale performance, the soil and climate must be able to produce and maintain proper vegetative cover (USEPA 1999). However, vegetation can have a negative effect on pollutant removal and can, along with any associated fertilization, increase nutrient loads (Yu et al. 2001). Another problem that occurs is resuspension which occurs more frequently during intense storm events, and can lead to a net export of pollutants (Yu et al. 2001).

Maintenance

As noted above, one contributor to pollutant export is mowing clippings left in the swale, as they can re-admit pollutants as the plant decomposes (Mazer et al. 2001). Consistent maintenance, such as mowing, can benefit swale treatment performance by removing the dissolved pollutants contained in the vegetation and increasing flow resistance by maintaining dense stands of grass (Mazer et al. 2001). In addition to picking up mowing clippings, other swale maintenance activities are required to ensure pollutant removal and reduced flow rates. One significant problem is scouring and channelization (Li 2015). Li (2015) studied 279 BMPs in Prince George's County, Maryland, to determine their effectiveness in reducing the effects of highway runoff, and found that 51% needed corrective action with 10% containing moderate to acute embankment erosion or scouring. Check dams and vegetated earth berms reduce erosion, but water still tends to cut into the soil around the check dams (Li 2015). Additional solutions to erosion include low longitudinal slope, wide channel bottoms, and geotechnical matting (Li 2015).

Swale Design Alternatives

Swale modifications such as check dams and filter strips can affect pollutant removal rates. Kaighn and Yu (1996) found that the use of a check dam had more influence on pollutant removal than the grade of the side slope. Check dams lengthen detention time and contact time which increases sediment and nutrient removal (Yu et al. 2001). During the low flow events for the test swale used by Yu et al. (2001), the check dam caused the detention time to nearly double. Of the mass of total phosporus, 98.6% was removed by adding check dams to a 274.5 m swale while average TP mass removal for swales longer than 75 m is 46.8%, and for a 30 m swale, removal increased (in comparison to a traditional swale design) for each of the pollutants when the check dam was added (Yu et al. 2001). Davis et al. (2011) also performed a study on two highway median swales ranging from 137 m to 198 m, and the study focused on the effects of check dams and filter strips. When check dams were used, the swale with the filter strip performed better than the swale without the filter strip with mean reductions of 62.7% and 27.1%, respectively (Davis et al. 2011). The swale with filter strip and check dam over-performed the no filter strip swale by an average of 18,000 L of runoff volume (Davis et al. 2011). Davis et al. (2011) suggest that observations should be made in swale design to determine the swale water depth where all the water is infiltrated and the swale water depth where no volume is reduced to indicate the swale's boundaries of volume reduction. Check dams enable the swale to reduce more runoff volume during moderate storm events by providing more storage and subsequent infiltration and evapotranspiration (Davis et al. 2011). Davis concluded that filter strips and in-line check dams should be added to grass swales to enhance performance (Davis et al. 2011).

Hydrology

Although many swale studies examine water quality, fewer studies have quantified volume reduction and flow attenuation. One study that produced quantifiable results was performed by Lucke et al. (2014) which observed the responses of four field swales handling 24 standardized synthetic runoff events. He found that the swales performed well at attenuating flow, finding a mean total flow reduction of 52% in 30 m long swales and a peak flow reduction of 61% (Lucke et al. 2014). Other authors have reported volume reduction ranging from 30 to 50% and peak flow reductions between 10 and 20% (Davis et al. 2011; Barrett 2008). One parameter that Lucke (2014) found to most affect total flow volumes, peak discharges, and infiltration rates was initial soil moisture content. This was corroborated by Barrett (2008), who found that optimal conditions could enable 50% of the runoff volume to be infiltrated in semiarid regions with permeable soil and low moisture content. Another significant factor in determining the infiltration storage capacity is soil compaction which can reduce capacity between 70 and 99% (Gregory et al. 2006).

Thus, parameters impacting infiltration potential include the timing and size of rain events and the available storage and length of the swale (Davis et al. 2011). Infiltration storage capacity declines asymptotically as the hydraulic conductivity of the soil increases which produces surface flow, then storage, and lastly discharge from the swale (Davis et al. 2011). During small storm events, complete or large runoff volume reduction is possible; but, during large storm events, soil saturation causes volume reduction to be small and at times, negligible (Davis et al. 2011). This has been shown in multiple studies. Deletic (2001) performed a study on grassed swales and filter strips and discovered similar results to Davis et al. (2011), observing a 45.7% reduction in runoff, with only 26 of the 52 simulated rain events producing runoff. Similarly, Yu et al. (2001) studied a 247.5 m swale with two check dams and found that it was able to handle large storm events through infiltration. Yu et al. (2001) reported 100% removal of pollutants for storm events below 1.27 cm (0.50 in). This value was higher than that observed by Kaighn and Yu (1996) who reported 100% infiltration for storms events below 0.5 (0.20 in) and 0.7 cm (0.28 in) for two 30 m swales. Since swales can completely infiltrate and manage pollutants for small storm events, Yu et al. (2001) recommended using swales in locations privy to light rainfall, as swales work better with long, low-intensity storm events. Regardless, studies suggest that swales have utility in other locations for the more frequently occurring smaller, less intense storms.

Davis et al. (2011) studied two potential design alternatives to increase infiltration in swales, vegetated filter strips (VFS) and in-line vegetated check dams. Davis et al. (2011) found that 36.5% of storm events were completely captured by the no-check dam swale, and 46.4% of storm events were completely captured by the check dam swale, as check dams significantly influence the ability of the swale to reduce runoff volume for moderate storm events. Davis et al. (2011) modeled the completely captured storm events, using a boundary equation, shown below in the *Complete Capture Section*. The complete capture depth ranged from 0.4 to 2.2 cm in Davis et al.'s study (2011).

Finally, it is important for the highway context to evaluate where the runoff infiltrates, in terms of distance from edge of pavement. Lancaster (2005) monitored 36 storm events in Pullman, Washington, and measured where the events infiltrated. Lancaster (2005) found that all runoff infiltrated within two meters from the edge of pavement for each of the events. At a second site in Spokane, Washington, of the 18 storm events observed, 12 storm events infiltrated water before 3.1 m, 5 events infiltrated runoff at 3.1 m, and only one event infiltrated runoff 6.2 m from the edge of pavement (Lancaster 2005).

Total Suspended Solids

Many factors cause differences in total suspended solids and nutrient removal rates; however, Winston et al. (2012) discovered that pollutant reduction is typically raised by increased swale length. In a review of literature, TSS reductions ranged from 29.7 to 99% with an arithmetic mean of 77% (Allen et al. 2015; Barrett et al. 1998a; Barrett et al. 1998b; Backstrom 2003; Deletic and Fletcher 2006; Kaighn and Yu 1996; Knight et al. 2013; Stage et al. 2012; Yousef et al. 1985; Yu et al. 2001).

Another explanation for the variability in removal percentages is differences in channel characteristics. Ferguson (1988) suggested that the length of swales should equate or exceed 60 m, while Yu et al. (2001) proposed a swale length of 75 m with a bottom slope at or below 3%. However, Barrett et al. (1998a) suggested that swale length is not as important if the stormwater traverses the side slope prior to entering the swale. Barret et al.'s (1998a) study examined two medians, positioned on major highways in Austin, Texas, to determine pollutant removal efficiencies and found that most of the pollutant removal took place on the swale's sides, which acted like filter strips. Vegetated filter strips are moderately sloped areas that allow stormwater runoff to travel via overland sheet flow (Barrett et al. 1998a). The vegetation acts as a filter, sedimentation and infiltration occur, and further filtration occurs through biological and chemical processes in the grass and soil (Barrett et al. 1998a).

Neibling and Alberts (1979) studied sediment removal in filter strips ranging from 0.6 to 4.8 m in length and found that up to 90% of the sediment was removed from simulated runoff. Clay particles were not removed as effectively, 37-83%; but, particles above 20 micronmeters were removed from even the shortest filter strip (Neibling and Alberts 1979). Deletic (2001) studied an experimental catchment that received runoff from a road inlet that was transported to a swale by a short pipe. Like Barrett et al. (1998a) and Winston et al. (2012), Deletic (2001) attributes sediment removal performance to rain depth, filter slope, grass length and density, and inflow sediment rate. Larger particles, above 57 micrometers were reduced by nearly 100%, while fine particles (0-5.8 micrometers) were reduced by 62.1% (Deletic 2001).

Barrett et al. (1998a), like Winston et al. (2012), emphasized the variability in pollutant removal by swales and filter strips. One circumstance that affected TSS removal in past literature was low input concentrations of TSS (Kaighn and Yu 1996). Runoff entering the swale from the buffer strip had average TSS concentrations of 38.7 and 32.8 mg/L, but when the runoff was sampled directly from the pavement, the TSS concentration was 112.9 mg/L (Kaighn and Yu 1996).

Nutrients

Swales have shown a variable ability for removing nutrients. Nutrient concentrations can be reduced along the swale due to infiltration, storage, plant uptake, and chemical/biological processes (Rushton 2001; Stagge et al. 2012). Deletic found that most of the nutrient reduction occurs in the first 25% of the swale's length (Deletic and Fletcher 2006). One of the reasons for the nutrient reduction occurring at the beginning of the swale is the ability of the soil to exchange cations with the nutrients which affects how quickly soil sorption occurs (Deletic and Fletcher 2006). Deletic and Fletcher (2006) also found that nutrient reduction is related less to flow than TSS reduction since TP typically attaches to fine sediment.

Stagge et al. (2012) performed a study on two swales located along a highway, one swale had a filter strip while the other did not. 50-60% of storm events in the study completely infiltrated (Stagge et al. 2012). Overall, the study found greater variability in the removal of nutrients than total suspended solids or heavy metals. Moderate removal of TN occurred for the majority of storm events; however, a few events exported nitrogen, 10-20% of summer events, showed seasonal variation in performance. Nitrite was reduced by 50.5-71.5% of mass (Stagge et al. 2012). The inclusion of a check dam improved the effluent concentrations of nitrate; however, check dams did not improve water quality for any of the other nutrients (Stagge et al. 2012).

There is large variability in phosphorus removal by swales (Stagge et al. 2012). Stagge et al. (2012) found that swales do not have a significant capability for reducing total phosphorus. The mean N-EMC concentrations were 0.55 and 0.34 mg/L at input, and the discharge values were 0.16-0.29 mg/L (Stagge et al. 2012). The swales treated stormwater with concentrations of TP larger than 0.7 mg/L, but were less effective in treating stormwater with lower TP concentrations (Stagge et al. 2012). Around 70% of phosphorus in runoff is bound to particulates, while 30% is in dissolved form (Stagge et al. 2012). The particulate bound phosphorus is attached to fine particles, around 11-150 microns in diameter (Stagge et al. 2012). Filter strips increased TP removal by 0.2 mg/L on average (Stagge et al. 2012). Additionally, check dams were not found to have an effect on TP removal (Stagge et al. 2012). Other studies found that TP removal ranges from 12-60% (Schueler 1994; Barrett et al. 1998a; Yu et al. 2001).

Finally, some studies have shown nutrient export from swales (Wu et al. 1998; Rushton 2001; Barrett 2005). One reason for variability in nutrient concentration is additional organic matter from grass or other vegetation, and materials gained from maintenance activities (Stagge et al. 2012). Filter strips contribute significantly to the increase of chloride by an average of 170 mg/L (Stagge et al. 2012), and highway swales export chloride, rather than decreasing it (Stagge et al. 2012). Stagge et al. (2012) found on average swales increase chloride by 36 to 203 mg/L.

Heavy Metals

Traffic-related activities produce metal elements and solids which mix with stormwater runoff after a storm event (Sansalone and Buchberger 1997). The metal elements either dissolve or are particulate-bound (Sansalone and Buchberger 1997). A study performed by Sansalone and Buchberger (1997) found that Zn, Cd, and Cu were soluble; whereas, Pb, Fe, and Al tended to be bound to particles. Metals result from the following sources: brakes, tires, automobile frame and body, fuels and oil, concrete pavement, asphalt pavement, de-icing salts, and litter (Sansalone and Buchberger 1997). Metal elements do not degrade in the environment, unlike organic compounds (Sansalone and Buchberger 1997). Numerous studies have been performed to determine the effects of highway traffic on water runoff quality (such as contamination by metals); with some studies analyzing water quality in relation to traffic intensity (Sansalone and Buchberger 1997).

Stagge et al. (2012) found that swales removed heavy metals in the following decreasing order of zinc, copper, lead, and cadmium which is supported by the studies of Schueler (1994) and Barrett et al. (1998a). Introducing check dams or filter strips into the system did not enhance heavy metal removal (Stagge et al. 2012). Since metals are largely bound to particulates in runoff, most metal reduction occurs through sedimentation and filtration (Morrison et al. 1983; Hallberg et al. 2007).

Modeling Efforts

Sediment Transport

For storm events that are not completely captured, Deletic (2001) models the trapping of sediment particles by grassed filter strips and swales. Deletic (2001) produced a model called TRAVA which examined runoff production and sediment transport. The model determines the particle size distribution of soil particles in the outflow (Deletic, 2001). The model was applied on an experimental catchment and found to be accurate and successful for three additional catchments (Deletic, 2001). A sensitivity analysis was performed by adjusting each of the following parameters while holding the other parameters in the model constant, length, slope, Manning's coefficient, surface retention, saturation hydraulic conductivity, water content of saturated soil, grass density coefficient, dispersion coefficient, and particle density (Deletic, 2001). Each of the adjusted parameters were put into dimensionless form to enable comparison (Deletic, 2001). The length of the strip affected runoff volume the most and had an exponential relationship (Deletic, 2001). The parameter that was next valuable to runoff volumes was hydraulic conductivity (Deletic, 2011). In regards to sediment transport, the length was the most important value with hydraulic conductivity significantly affecting sediment transport, as well (Deletic, 2001). Creating TRAVA enabled Deletic (2001) to evaluate the importance of parameters in terms of sediment reduction and runoff volume.

Identifying the importance of parameters allows designers to know which parameters to adjust to meet runoff reduction and sediment removal standards.

Complete Capture

Several modeling efforts have been made to inform and predict swale treatment processes. Davis et al. (2011) modeled the complete capture threshold by plotting total rainfall vs. storm duration, thus revealing the separation between completely captured storm events and storms producing runoff (Davis et al. 2011). The same boundary equation modelled swales with no check dam and swales with a check dam.
To model the complete capture threshold Davis et al. (2011) identified the following boundary equation,

$$P = 0.07 \times D + 0.35 \text{ cm},$$

where P is total rainfall in cm and D is the storm duration in hr.

To account for rainfall on the road surface that cannot infiltrate, an area adjustment was made to produce the following equation:

$$P\_swale = 0.112 \times D + 0.56 \text{ cm},$$

where P is the adjusted total rainfall in cm and D is the storm duration in hr (Davis et al. 2011). Davis et al. (2011) observed the average infiltration rates ranged from 0.3 to 1.5 cm/hr for captured storm events, and the slope of the equation, 0.112 cm/hr, symbolizes the steady state infiltration rate. This value was found to be comparable to the saturated hydraulic conductivity values for the loam and sandy loam soils in the area, 0.34 and 1.09 cm/hr respectively (Davis et al. 2011).

By modeling typical Maryland design storm events, representing variability in rainfall depth and duration, Davis et al. (2011) found that an average of 59% of storm events would be completely captured in an average year. Davis et al. (2011) found that swale probability plots help to identify where complete capture changes to flow conveyance. For the Maryland storm events, the change occurred at a discharge volume of 1 x 10^5 L, which is equivalent to a 3.7 cm (1.5 in) rainfall depth, which falls above the threshold identified by Kaighn and Yu (1996) and Yu et al. (2001). Davis et al.'s (2011) equation identifies the runoff volume that is completely captured and thus, the volume that 100% pollutant removal occurs (which is important when designing swale geometry).

WinSLAMM

Source Loading and Management Model for Windows (WinSLAMM) was developed to model and analyze projects of varying scale including: large scale (city-wide) projects, site development projects, and single practices (Paschke et al., unpublished manual, 2017). The analysis accounts for the land uses and site characteristics, determines the current runoff volumes and pollutant loads, and evaluates stormwater controls by calculating the volume and pollutant reduction (Paschke et al. 2017). The model's development started in the mid-1970's, and the model started being used in state water quality regulatory agencies in the mid-1980's (Paschke et al. 2017). The model is based on data collection from actual sites at varying scales and conditions (Paschke et al. 2017). Since the research values did not mirror stormwater assumptions, the first adaptations focused on smaller scale projects until more data became available (Paschke et al. 2017). Inputs for the program include: parameter files, land use type and area, size of all source areas, source area characteristics (soil type, connected imperviousness, street texture, etc.), and control practice designs (Paschke et al. 2017). Data files and calibrated parameter files are used such as rainfall file, runoff coefficient file, particulate solids concentration file, pollutant probability distribution file, and particle size parameter file (Paschke et al. 2017). These files are based on extensive research resulting from a specified location (Paschke et al. 2017). WinSLAMM is unique since it determines the runoff volume and pollution loading for every source area within a land use for each rainfall event (Pitt 2013). Areas are not lumped together which enables the highest loading areas to be identified and prioritized (Pitt 2013). WinSLAMM is valuable since the model can be used to show which site parameters are most important for different site goals. The model can be used to isolate parameters to determine their importance so that swale design can be optimized.

Objectives

Despite the number of studies performed on vegetated swales, there are still gaps in knowledge regarding their performance. In particular, this is the case for volume reduction, where a smaller number of studies have been performed relative to water quality. Also, studies have shown there are many different parameters that affect swale treatment processes, including infiltration rate, soil compaction, swale geometry, type of vegetation, and annual average daily traffic of the roadway. Thus, studies performed in variable locations are needed to understand swale performance. The objectives of this study include: (1) evaluating swale performance for volume and pollutant reduction at a unique location in literature, and (2) model the swale in WinSLAMM to determine its ability to be provide accurate volume reduction estimates.

CHAPTER TWO
MATERIALS AND METHODS

Study Area

The project site is in Knoxville, TN, in the median of Asheville Highway located near the intersection of Lecil Road, see Figure 2.1. Asheville Highway is a four-lane divided highway with an average annual daily traffic of approximately 27,378 vehicles, (KGIS 2017). The site was chosen based on longitudinal slope, median width, and average annual daily traffic. Two swales connected in series by a pipe over a length of 1498 feet drain stormwater runoff from the highway. The catchment area treated by the swales is 69,260 square feet, with 41,101 square feet of pervious area (including the swale) and 28,077 square feet of impervious area, making the contributing area 40.6% impervious and 59.4% pervious. The pervious area is made up of loam and silt loam soils, (USDA 2017). According to TDOT Standard RD01-S-11A, sod ditches are seeded with vegetal retardance classification “C” and are scarified prior to seeding (TDOT 2002, 2015). The longitudinal slope of the upper swale is 2.5%, while the longitudinal slope of the lower swale is 1.0%.

Runoff Quantity Monitoring

Monitoring equipment was installed during the summer of 2016. The flume immediately preceded the swale’s outlet, a storm drain outfall. Concrete was used to secure the flume and led to the flume’s approach to prevent flow under the flume. Wingwalls were constructed to direct the flow into the flume and to prevent flow from traveling around the flume. At the outlet, an ISCO 6712 equipped with a 730 Bubbler Flow Module was connected to the flume allowing collection of both water quality samples and stage data (converted to flow via standard equations). The sampler was programmed to collect four flow-paced samples per bottle. Flow data was recorded every minute. A slot drain was installed along the roadway to obtain runoff directly from the road. An ISCO 674 rain gauge was installed and connected to an ISCO 4230 flow meter, allowing triggered

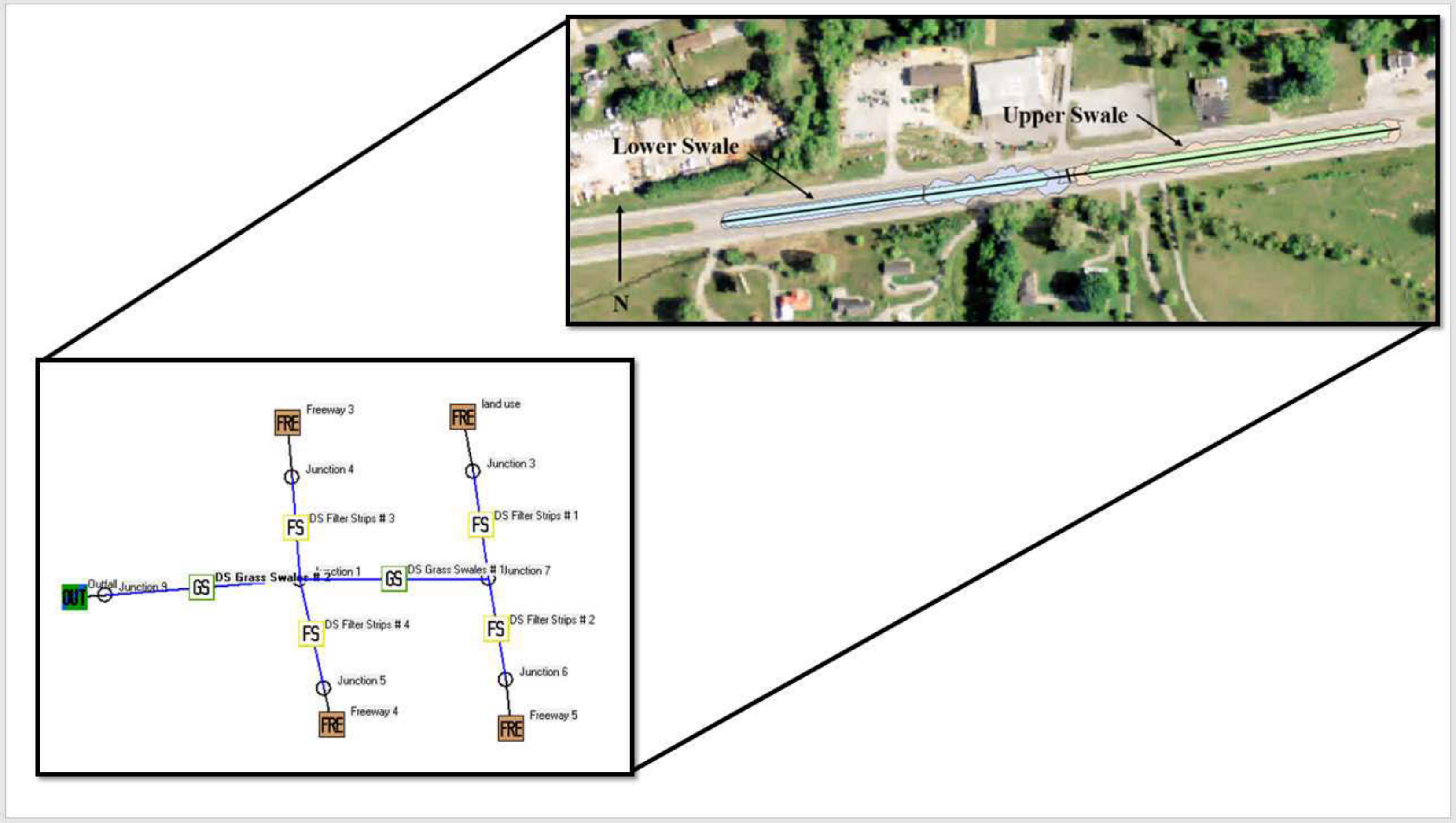

Figure 2.1: Project site figure showing aerial view of swale and associated catchment, and the WinSLAMM model representation of the site

sampling of the roadway runoff by an ISCO 3700 sampler. The sampler was triggered by 0.05 inches of rain occurring over 15 minutes. The sampler was time paced to take samples every 5 minutes after the sampler was triggered. Each bottle collected 4 samples. The rain data was recorded every 5 minutes.

Water Quality Monitoring

Composite samples for the outlet and the inlet were formed by subsampling a volume from each sample based on its percentage of the total storm. Analyses were performed for total suspended solids, nutrients, and metals. Total suspended solids were quantified, using the SM 2540 D filtration method (APHA, 2005). IC (Ion Chromatography, Method 300.1 – anions and cations) and ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometry, Method 200.7 – trace metals) analyses were performed on samples filtered by 0.45 micrometer filters to determine the amount of nutrients (chloride, nitrite, nitrate, sulfate, hydrogen phosphate, and ammonium) and metals (copper, zinc, and lead) in the samples, respectively. The IC tests were performed within a 28-day hold time, and the ICP tests were preserved by a dose of nitric acid and performed within a 6-month hold time. The measured detection limits for each pollutant are in Table A.1. The composite samples were held in refrigeration until they were analyzed for water quality. After tests were performed, the sample bottles were rinsed and submerged in a hydrochloric acid bath for 2 hours. Afterwards, each bottle was rinsed three times.

Rainfall Volume Calculations

To calculate the rainfall volume, initial abstraction was considered to be 0.05 inches of the impervious area's rainfall; thus, the rainfall over the roadway was reduced by 0.05 inches before multiplying it by the impervious area, while the total rainfall amount was multiplied by the pervious area. To calculate the total rainfall volume, the impervious and pervious rainfall volumes were added together.

Modeling

WinSLAMM was selected to model the vegetated swale due to its established usage for green infrastructure practices and land uses. The model was used by Hurley and Forman

(2011) to model ponds and biofilters and by Borris et al. (2016) to model two urban catchments of mixed land use which included green spaces. The model's parameter files are based on extensive data collection. WinSLAMM models the effects of stormwater controls on land uses by determining the runoff volume for each source area. WinSLAMM provides continuous simulation while allowing the user to modify input values for calibration to measured results. For this study, only stormwater volume was modeled, calibrated, and analyzed for performance using collected site data. Hourly rainfall depths collected from the site were used to populate the rainfall parameter file, and antecedent moisture content was calculated based on the rainfall file. Other parameter files remained as model suggested values based on the site's location in the southeastern United States.

To best model the site in WinSLAMM, the contributing area was divided into four catchments. The site was divided between the upper and lower swales and subdivided into northern and southern sections (one on each side of the road). The catchment areas were determined by processing the digital elevation model in ArcGIS (see Figure 2.1). Land use calculations were then made. Each catchment was made up of a freeway area (the roadway) and a large turf area (the median). The large turf area consisted of the filter strip and the grass swale. To distinguish between the filter strip and swale, the area inundated by a 5-year frequency storm with a duration of 24 hours was used as the boundary condition. This storm would produce a flow resulting in a depth of 0.703 feet in the trapezoidal median, filling the trapezoid to a top width of 11 feet. This area was taken as the extent of the swale, while the remaining area makes up the filter strip. The parameters for each control were input into WinSLAMM. The swale and filter strip lengths and longitudinal slopes and swale side slopes were determined using the measurement tools of ArcGIS and the digital elevation model, while the bottom width, grass height, and grass type were determined based on field measurements.

Infiltration Measurements

Infiltration rates at the site were determined by conducting field tests using double-ring tests were performed on the northern filter strip, southern filter strip, and grass swale, see Table A.2. Graphs of the results from the DRI tests were used to determine the point at which the infiltration rates reached an equilibrium. WinSLAMM requires the dynamic infiltration rate which is equivalent to the measured static infiltration rates divided by two (PV & Associates 2015). The site's measured infiltration rates and dynamic infiltration rates are shown in Table 2.1. High variability was noted for the site as has been shown in other studies of highway green space. The infiltration rates of the side slopes varied from those at the center of the swale, and the measured infiltration rates were higher than WinSLAMM's defined infiltration rates for loam and silt loam soil types (the predominate soil type in the surrounding area). Ahmed et al. (2015) obtained similar results from a roadside swale study. Large differences were observed between the side slopes and center of the swale's geometric mean (Ahmed et al. 2015). Ahmed et al. (2015) also observed that soil texture class did not have a statistically significant effect on the mean field-saturated hydraulic conductivity of a swale which supports the observation of higher measured infiltration rates than implied by the soil type.

Table 2.1: Measured and Dynamic Infiltration Rates

	Upper Right	Upper Middle	Upper Left
Measured Infiltration Rate (in/hr)	5.37	1.35	2.07
Dynamic Infiltration Rate (in/hr)	2.69	0.67	1.036
	Lower Right	Lower Middle	Lower Left
Measured Infiltration Rate (in/hr)	3.97	2.15	1.46
Dynamic Infiltration Rate (in/hr)	1.98	1.08	0.73

CHAPTER THREE

RESULTS AND DISCUSSION

Data Summary

Data was collected for 11 months from August 18, 2016 until July 18, 2017, with 65 rainfall events monitored. The average rainfall event was 0.69 inches with a minimum rainfall of 0.11 inches and a maximum rainfall of 5.47 inches. Summary statistics of the data collection are given in Table 3.1. The rainfall events were distributed over the four seasons with the most (40%) occurring during spring and the least (6%) occurring during autumn.

Water Quantity Results

Rainfall-outflow data are shown in Figure 3.1, where a mostly linear relationship was observed. There are two potential outliers in the data due to a lack of agreement between the rainfall-outflow trend and these particular data points. These were the largest two events monitored, the 5.47-inch storm showed substantially less outflow than expected, while the 3.87-inch storm showed substantially more. The runoff volumes from both events were removed from further analysis as there appeared to be monitoring error, see Figure 3.2. Table A.3 displays the rainfall volume, runoff volume, and percent runoff reduction of each monitored event. The swale's hydrologic performance exceeded what has been seen in previous literature. The swale's mean runoff reduction was 87.2%, while the percent runoff reduction ranges from 30-52% in literature (Backstrom 2003; Barrett et al. 1998b; Lucke et al. 2014; Deletic 2001; Rushton 2001). Figure 3.3 displays the percent runoff reduction plotted with the rainfall totals. 96% of rainfall events below 0.5 inches exceeded 80% runoff reduction. Davis et al. (2011), Deletic (2001), and Yu et al. (2001) observed similar runoff reduction with complete capture occurring for small storm events, ranging from 0.16 – 0.87 inches. 15 rain events ranging from 0.11 to 0.93 inches approached complete capture, by producing less than 50 cubic feet of runoff. The range of measured rainfall depth producing complete capture is very close to Davis et al.'s (2011) range. Rainfall events below 0.5 inches varied between complete capture and

Table 3.1: Data Collection Summary Statistics

Summary Statistics	
No. of Rainfall Events	65
Average Rainfall (in)	0.69
Max Rainfall (in)	5.47
Min Rainfall (in)	0.11
No. Sampled for Water Quality	
Inlet	33
Outlet	35
No. of Rainfall Events per Season	
Spring (March 1 - May 31)	26
Summer (June 1 - August 31)	14
Autumn (September 1 - November 30)	4
Winter (December 1 - February 28)	21

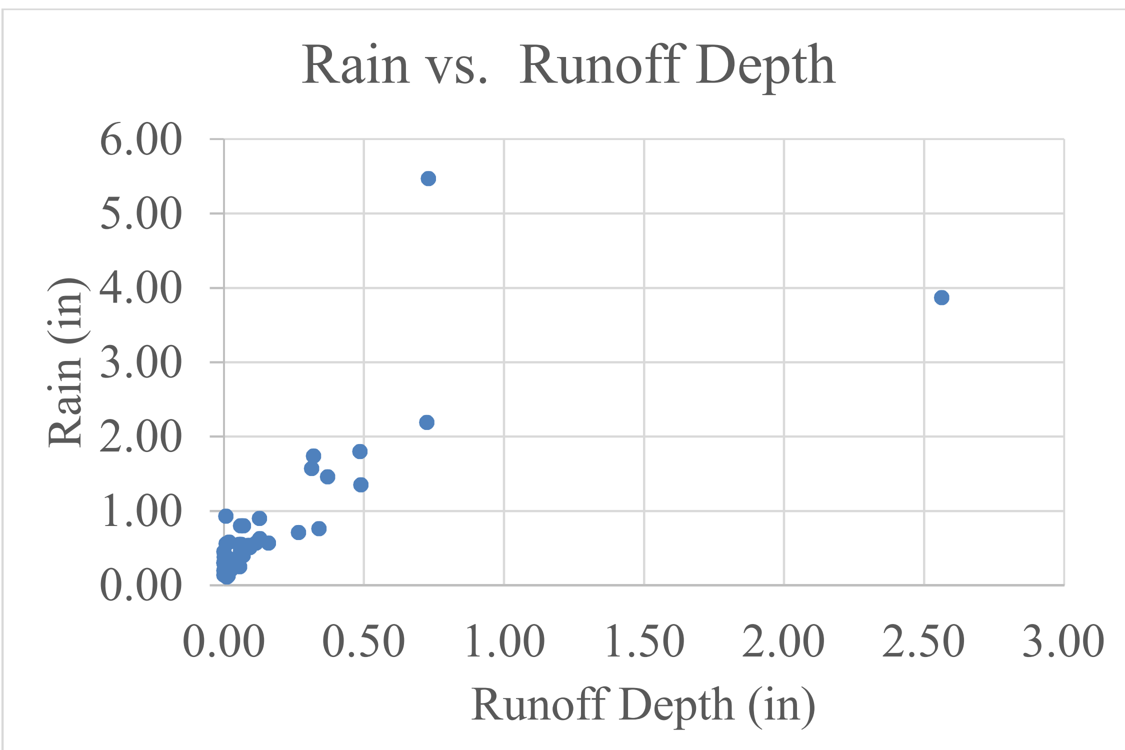

Figure 3.1: Rainfall-Outflow Data

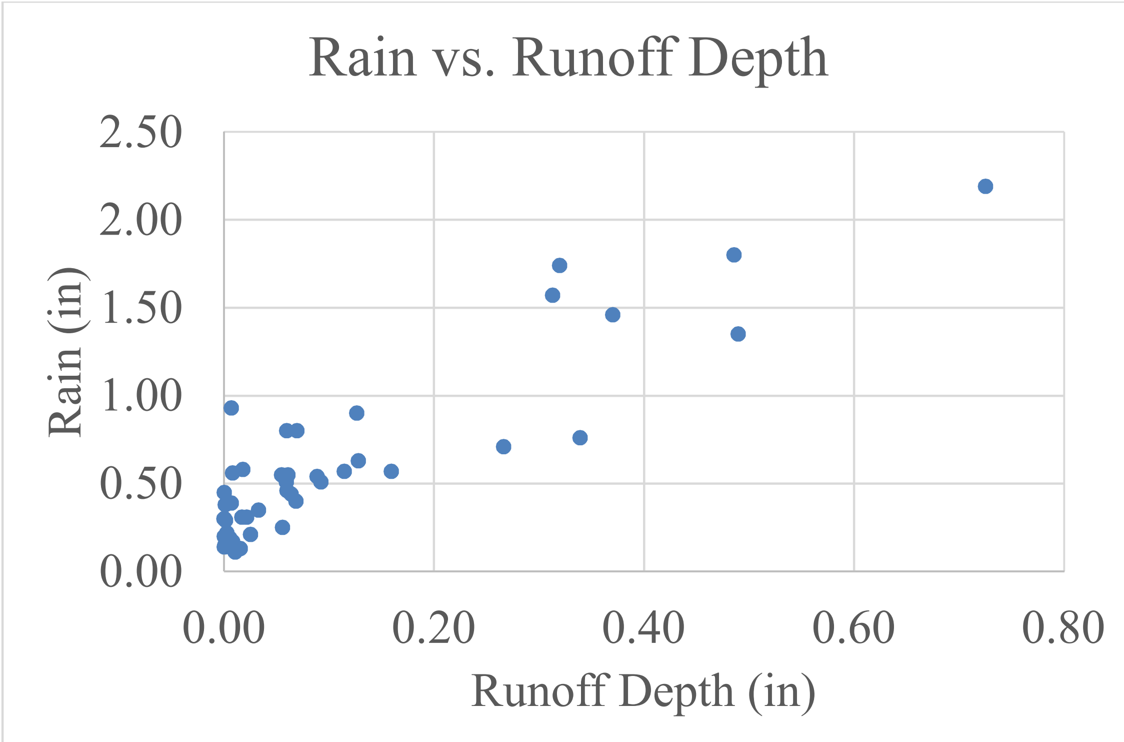

Figure 3.2 Rainfall-Outflow Data with Outliers Removed

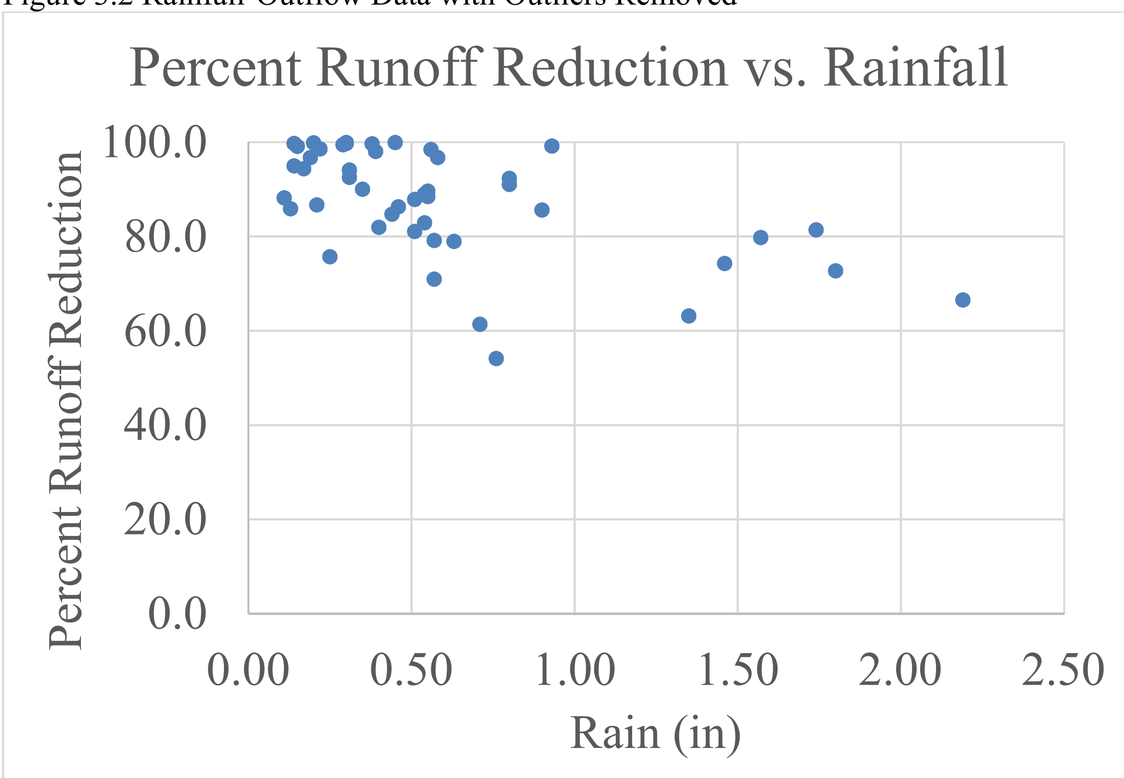

Figure 3.3: Percent Runoff Reduction

producing a runoff volume of approximately 500 cubic feet. This performance variability could be a result of the soil's antecedent moisture content at the time of the event.

Total Suspended Solids

The swale reduced TSS better than expected, Figure 3.4. The mean TSS value for the swale's outlet is 7.10 mg/L, while the mean TSS value measured directly from the slot drain is 79.0 mg/L, see Table 3.2. The TSS reduction percentage is 91.0% which falls near the upper limits of the 29.7 to 99% reduction range in literature (Allen et al. 2015; Barrett et al. 1998a; Barrett et al. 1998b; Backstrom 2003; Deletic and Fletcher 2006; Kaighn and Yu 1996; Knight et al. 2013; Stage et al. 2012; Yousef et al. 1985; Yu et al. 2001). Two explanations for high TSS reduction are the length of the swale and the presence of side slopes. Deletic (2001), Ferguson (1998), Winston (2012), and Yu et al. (2001) prioritized swale length as one of the most important parameters for TSS reduction. They suggested that swales should exceed 60-75 m which is met by the site's 457 m swale. Barrett et al. (1998a) found that side slopes were more influential on TSS reduction than swale length. The Asheville Highway swale has both conditions noted in literature as important, a length meeting recommendations and side slopes, which could be the primary explanations for the swale's effectiveness in TSS reduction. Deletic (2001) also found hydraulic conductivity to be a significant factor affecting TSS reduction. Erosion around the slot drain occurred and led to soil build-up near the sampler at times, which could cause inflated TSS inlet values, explaining the high reduction rate. The swale reduced TSS to an average outlet concentration on the lower limit of the range seen in literature (Barrett et al. 1998a; Barrett et al. 1998b; Knight et al. 2013; Stagge et al. 2012).

Nutrients and Chloride

Some unexpected results occurred for nutrient and chloride concentrations. Each pollutant was plotted, displaying the concentration vs. date. The graphs of ammonium, chloride, and nitrite in Figures 3.5 - 3.7 show an increase in each pollutant's concentration, following a rain event on January 10, 2017. Two snow events occurred on

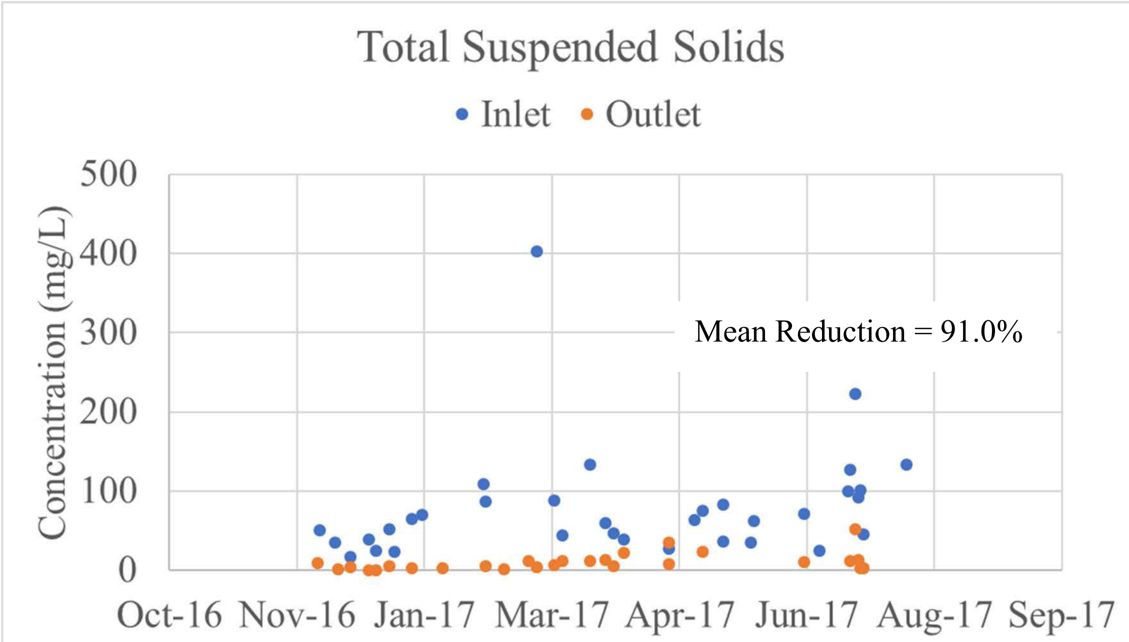

Figure 3.4: TSS Inlet and Outlet Concentrations

Table 3.2: TSS Summary Statistics

Statistics		**TSS**
Measured Inlet	Mean (mg/L)	79.0
	Median (mg/L)	63.0
Measured Outlet	Mean (mg/L)	7.10
	Median (mg/L)	4.51
Reduction Percentage (%)		**91.0**
Literature Inlet	Mean (mg/L)	28.6* - 190
Literature Outlet	Mean (mg/L)	7.0 - 35.0

Literature values from the following sources Barrett et al. (1998a), Barrett et al. (1998b), Knight et al. (2013), GSWWE (2017), Pitt and Maestre (2005), and Stagge et al. (2012). Bold value indicates significant difference between inlet and outlet. *Indicates a median value.

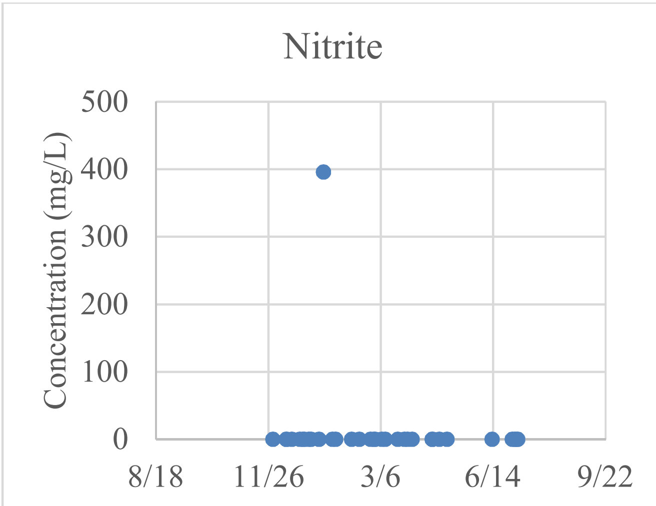

Figure 3.5: Nitrate Concentrations

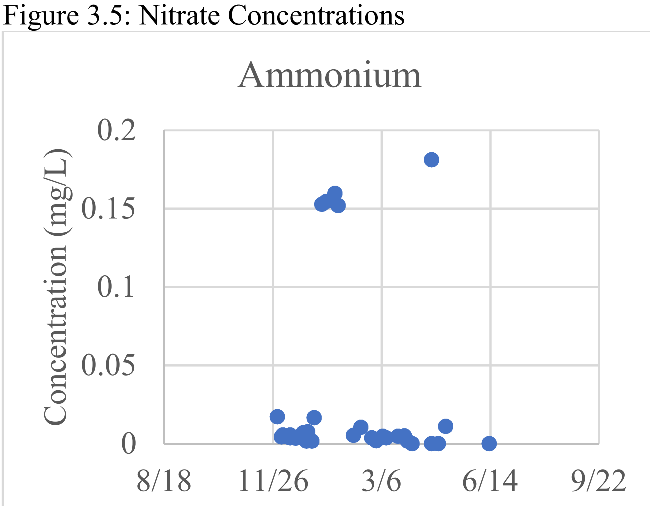

Figure 3.6: Ammonium Concentrations

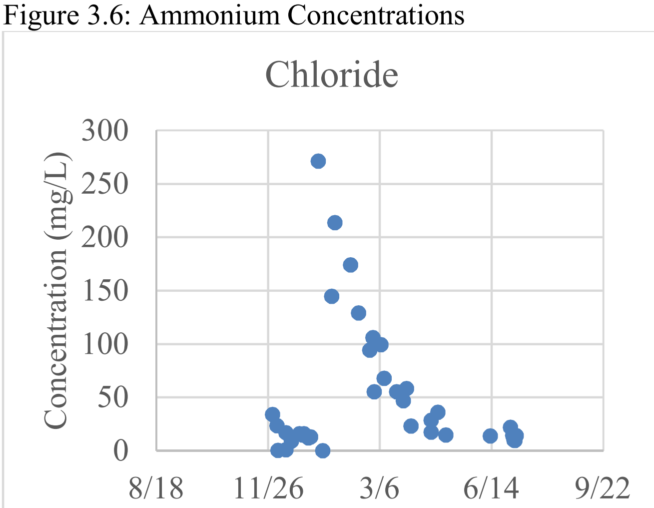

Figure 3.7: Chloride Concentration

January 6th and 7th, and the roads were treated with salt brine to prevent icing. The January 10th rain event was the first rain event after the salt brine was applied. The concentration of nitrate reached equilibrium after one rain event and ammonium flushed out of the system after 5 rain events. Chloride took much longer to reach equilibrium, 17 rain events. The concentration of chloride remained elevated until rain event 35 on March 30, 2017. Each of the elevated concentrations following the salt brine application were removed from the analysis as to avoid bias due to these snow events. Figures 3.8 – 3.10 show the concentrations with the outliers removed. By removing the pollutant concentrations affected by the salt brine, the means and medians of the affected pollutants are reduced. Table 3.3 shows the summary statistics for the inlet and outlet nutrient and chloride concentrations. The reduction percentage was calculated to assess performance, and the Wilcoxon rank sum test was performed to determine if there was a significant difference between the inlet and outlet. Ammonium and nitrite-nitrate were reduced, while chloride and phosphate experienced an export of pollutants. Pitt and Maestre (2005), Stagge et al. (2012), and Barrett (1998b) performed previous studies, quantifying higher inlet concentrations than the site's measured values, see Table 3.3. Inlet pollutant concentrations are known to influence pollutant reduction percentages (Stagge et al. 2012). If the inlet concentrations are too low, the swale is unable to reduce the concentrations further. This suggests the influence of irreducible concentrations, which has been discussed in literature for other SCMs (Hathaway and Hunt 2010). Schueler and Holland (2000) performed a study to establish ranges for irreducible concentrations and found nitrate-nitrogen to be irreducible at 0.7 mg/L for wet ponds and pond/wetland systems which is higher than the Asheville Highway Site's inlet value (Schueler and Holland 2000). The inlet concentrations for ammonium, chloride, nitrite-nitrate, and phosphorus are much lower than the concentrations seen in literature. The pollutant inlet concentrations could be too low for the swale to reduce the pollutants further, and the organic matter from the vegetation could increase the nutrient concentrations as it breaks down and is processed into other nitrogen forms. Figures were made to compare the inlet and outlet concentrations at the Asheville Highway site with the average mean concentrations from literature, see Figures 3.11 –3.13. The figures show how low the

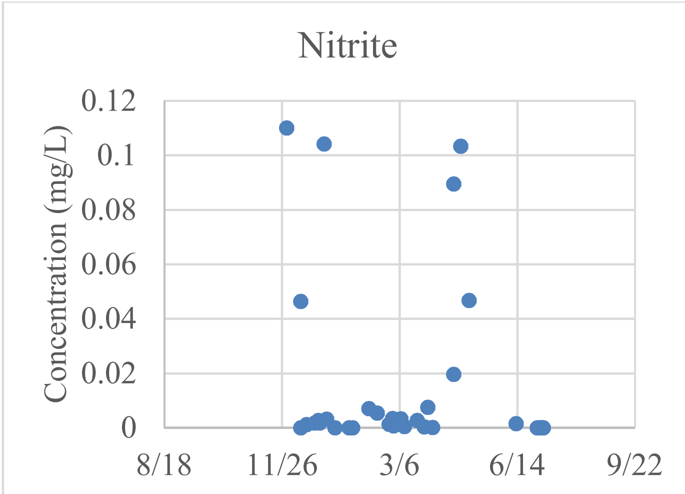

Figure 3.8: Nitrate with Elevated Concentration Removed

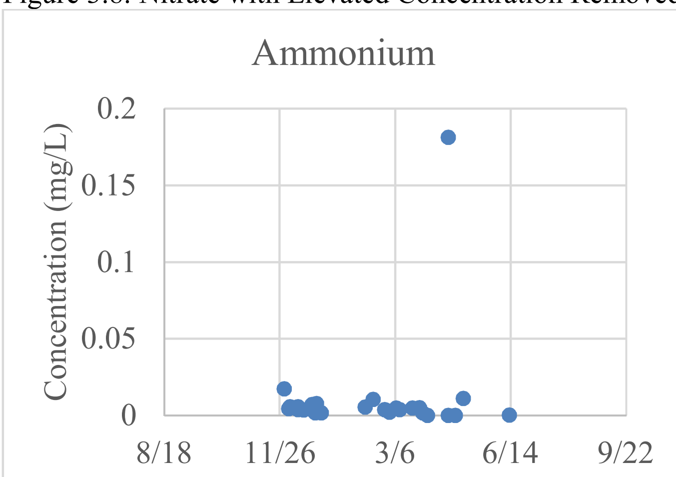

Figure 3.9: Ammonium with Elevated Concentrations Removed

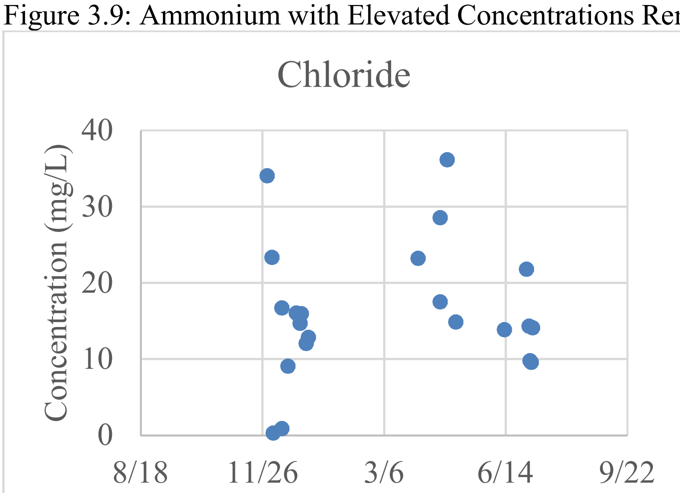

Figure 3.10: Chlorine with Elevated Concentrations Removed

Table 3.3: Nutrient and Chloride Summary Statistics

Statistics		NH4+	CL	NO2+NO3	PO4
Measured Inlet	Mean (mg/L)	0.028	1.177	0.116	0.036
	Median (mg/L)	0.002	0.878	0.084	0.008
Measured Outlet	Mean (mg/L)	0.011	16.357	0.112	0.037
	Median (mg/L)	0.002	0.878	0.084	0.008
Reduction Percentage (%)		59.5	**-1289.7**	**3.94**	-3.73
Literature Inlet	Mean (mg/L)	1.07*	19 - 123	0.26*	0.03*
Literature Outlet	Mean (mg/L)		68	0.31*	0.11*

Literature values from the following sources Barrett et al. (1998a), Barrett et al. (1998b), Knight et al. (2013), GSWWE (2017), Pitt and Maestre (2005), and Stagge et al. (2012). Bold value indicates significant difference between inlet and outlet. *Indicates a median value.

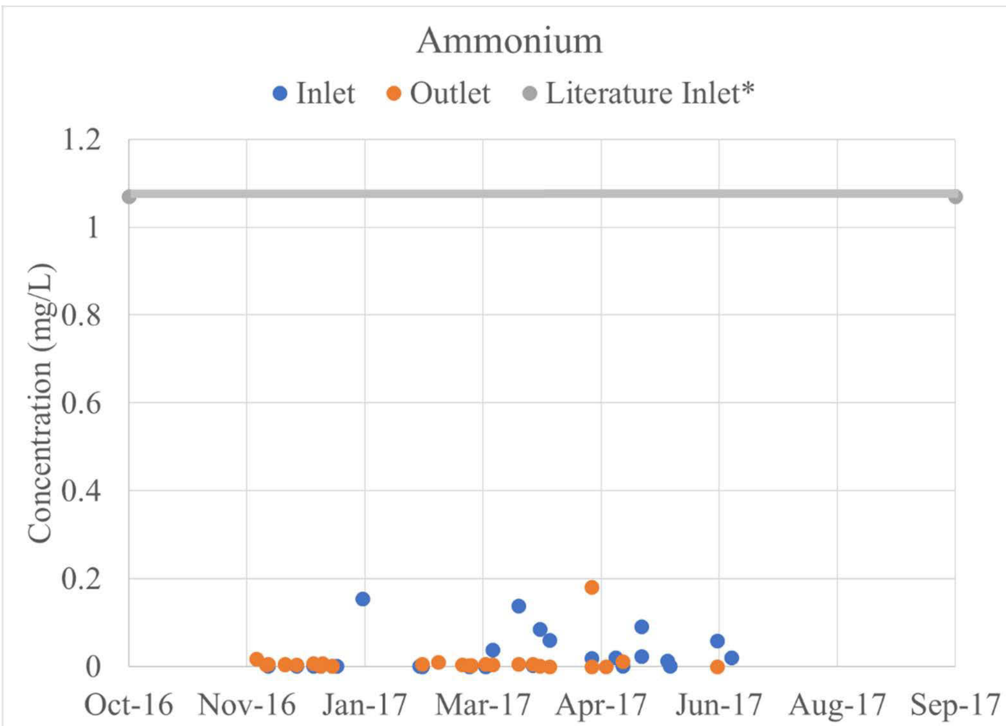

Figure 3.11: Inlet and Outlet Ammonium Concentrations
*Literature inlet concentration is based on the median.

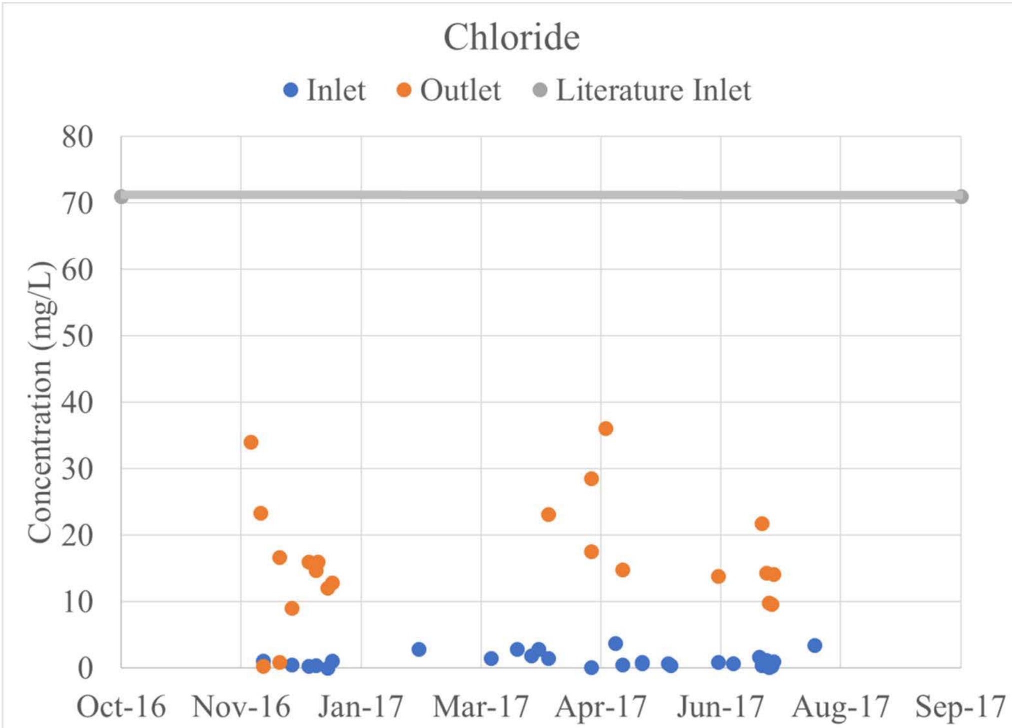

Figure 3.12: Inlet and Outlet Chloride Concentrations

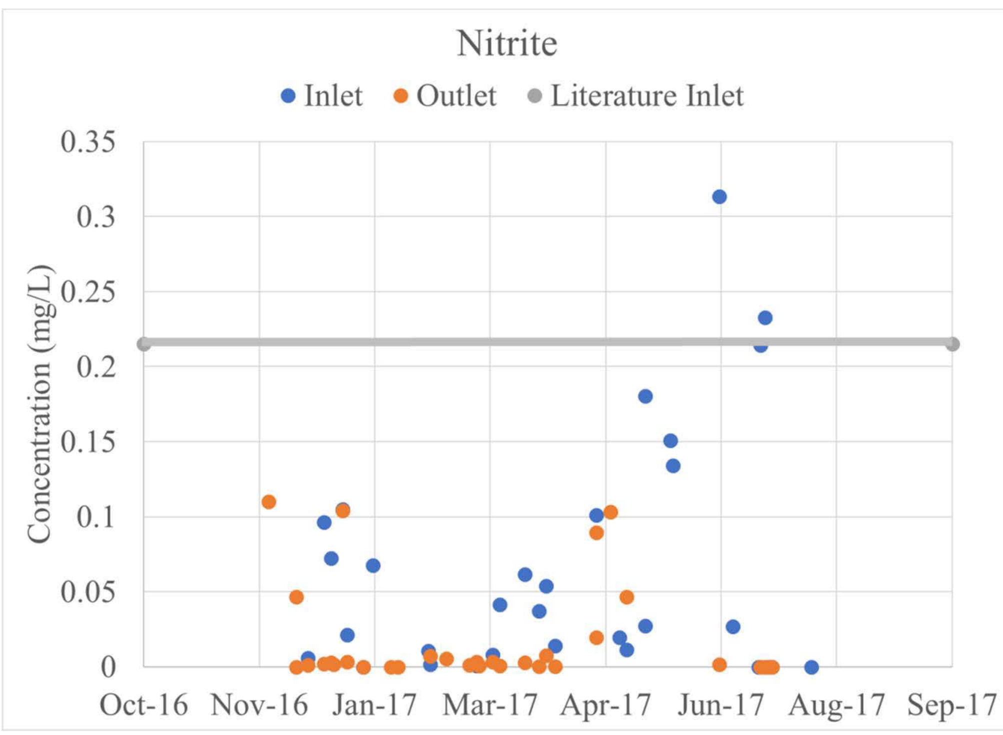

Figure 3.13 Inlet and Outlet Nitrite Concentrations

inlet concentrations are compared to the inlet concentrations in literature. The second possibility for low inlet concentrations is that the sampling location is causing artificially low concentrations not representative of the entire contributing catchment. Sampling in one location from the edge of pavement is not representative of sheet flow along the entire length of the edge of pavement. Also, the road crowns at a point in the inside lane, causing the bulk of the traveled area to drain into the side slopes, rather than the median which could cause lower concentrations of pollutants to flow into the slot drain, see Figure A.2. Table 3.3 shows that the site's outlet values are much lower than outlet values found in literature (Barrett et al. 1998a; Barrett et al. 1998b; Knight et al. 2013; GSWWE 2017; Pitt and Maestre 2005; Stagge et al. 2012). The mean outlet concentration of chloride from literature is 68 mg/L; however, the site's mean outlet concentration is 16.4 mg/L. The outlet concentration that varied the most from literature is phosphate with a measured median concentration of 0.008 mg/L while literature reports a median outlet concentration of 0.11 mg/L.

Heavy Metals

In addition to the export noted for the nutrient species, the swale appeared to export heavy metals. Table 3.4 shows inlet and outlet concentrations for metals as well as the percent change. The primary explanation for the net increase of all three heavy metals is low inlet concentrations caused by irreducible concentrations, inlet sampling at one location, and/or the superelevation of the road. As noted above, runoff from the highway sheet flows into the swale, making representative inlet monitoring impossible. Instead, one small portion of runoff was chosen for monitoring, and it is possible that the location chosen had lower concentrations relative to the other contributing areas. A range of inlet and outlet concentrations from Barrett et al. (1998a), Barrett et al. (1998b), GSWWE (2017), Knight et al. (2013), and Pitt and Maestre (2005) are recorded in Table 3.4 for copper, lead, and zinc. The inlet and outlet concentrations from literature are lower than the measured inlet and outlet concentrations. Figures 3.14 – 3.16 illustrate how low the measured concentrations are by comparing with Pitt and Maestre's (2005) median concentrations for freeways. Pitt and Maestre's (2005) study examined inlet

Statistics		Cu, filtered	Pb, filtered	Zn, filtered
Measured Inlet	Mean (µg/L)	2.703	0.268	12.218
	Median (µg/L)	1.942	0.152	7.111
Measured Outlet	Mean (µg/L)	4.698	2.100	15.048
	Median (µg/L)	4.015	1.825	9.913
Reduction Percentage (%)		**-73.8**	**-683.2**	-23.2
Literature Inlet	Mean (µg/L)	6.50* - 20.0	1.30* - 138	34.2* - 347
Literature Outlet	Mean (µg/L)	5.63*	1.05 - 82	19.9 - 90

Table 3.4: Inlet and Outlet Heavy Metal Concentrations

Literature values from the following sources Barrett et al. (1998a), Barrett et al. (1998b), Knight et al. (2013), GSWWE (2017), Pitt and Maestre (2005), and Stagge et al. (2012). Bold value indicates significant difference between inlet and outlet. *Indicates a median value.

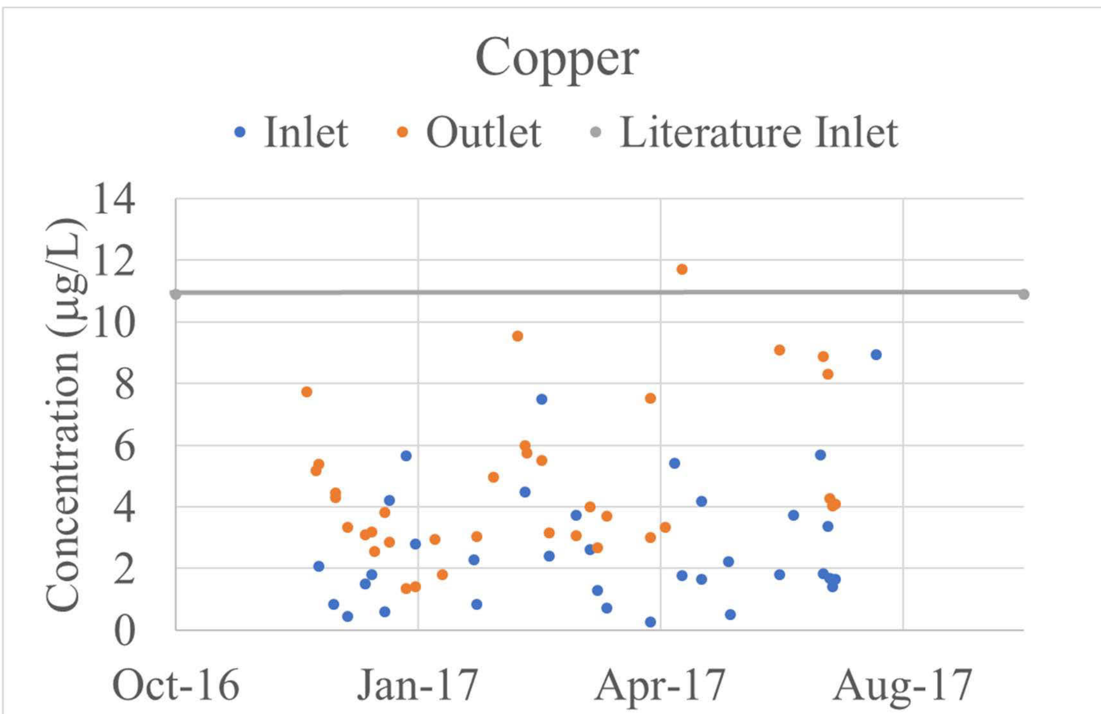

Figure 3.14: Copper Inlet and Outlet Concentrations

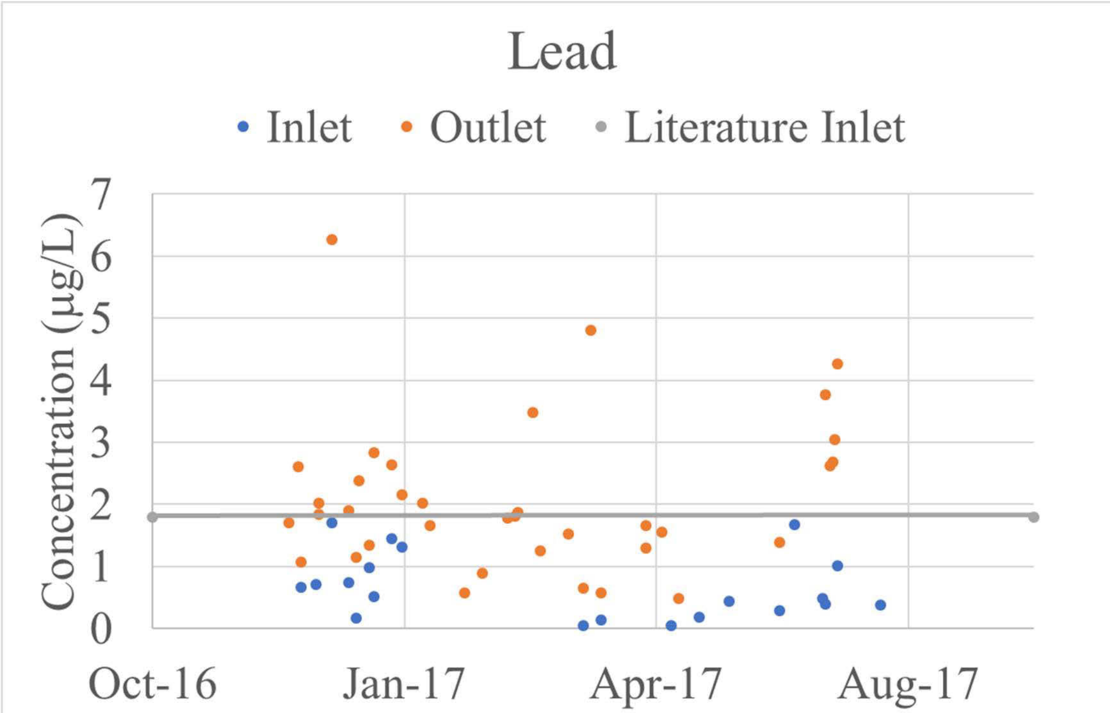

Figure 3.15: Lead Inlet and Outlet Concentrations

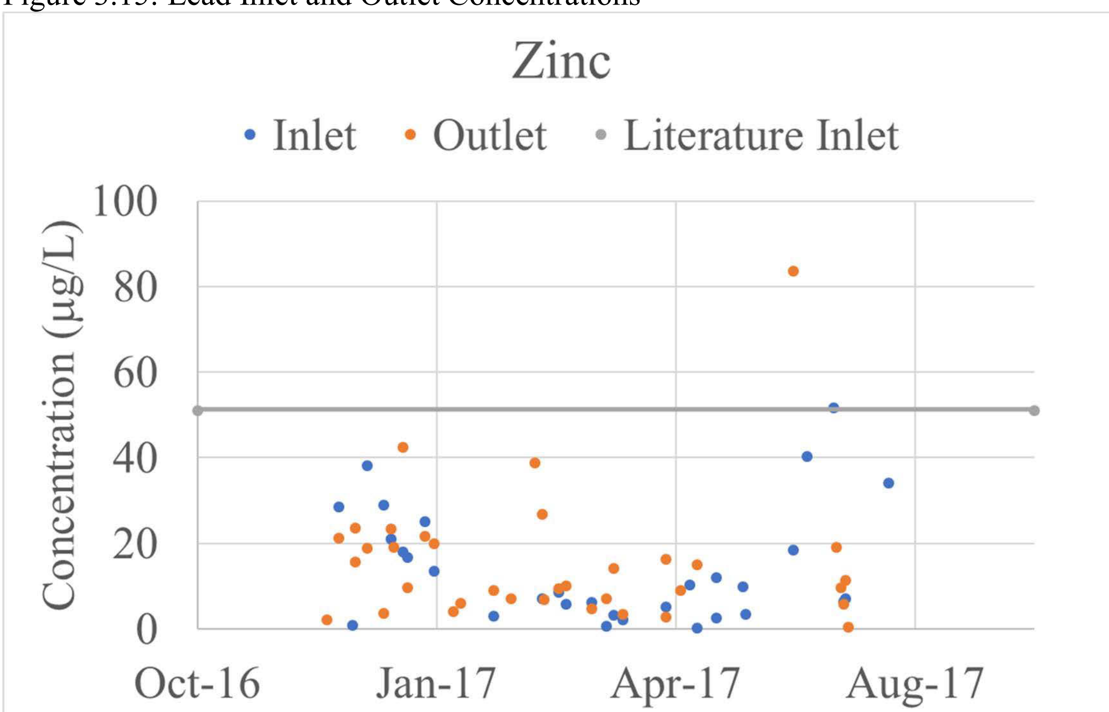

Figure 3.16: Zinc Inlet and Outlet Concentrations

concentrations for more than 104 freeway sites. The hypothesized irreducible concentrations lead to a net export of each heavy metal. The Wilcoxon rank sum test was performed to determine if there was a significant difference between the inlet and outlet concentrations. There is a significant difference for copper and lead, but not for zinc. Also, the measured outlet concentrations for lead and zinc are lower than the range seen in literature, and the measured concentration for lead is on the lower limit of the range. According to the Tennessee Department of Conservation's (TDEC) General Water Quality Criteria the dissolved concentrations of copper, lead, and zinc must not be continuously higher than 9.0, 2.5, and 120 μg/L, respectively to protect fish and aquatic species health (TDEC 2013).

WinSLAMM Output

To model the site, variables were inputted to define the filter strips and the swale, such as soil type, compaction type, grass height, control practice length, and longitudinal slope. Due to the high longitudinal slope of each filter strip (>0.05), WinSLAMM removed 10 feet from the length of the filter strip, which is the entire length of the filter strip for the Asheville Highway site (PV & Associates (2015). Thus, the lack of filter strip representation in the model is likely a source of some error. Other characteristics of the catchment and swale were set to measured values or literature values as noted above.

The model was found to provide runoff values too low in comparison to those measured using dynamic infiltration rates of 0.67 and 1.08 based on on-site measurements for the upper swale and lower swale, respectively (Table 2.1). This suggests that either the catchment was providing more flow to the system than the model predicted, or that the swale was retaining less water than the model predicted (i.e. the infiltration rate was too high). Since runoff was only measured at the outfall and not quantified at the edge of pavement, the runoff coefficients could not be calibrated to observed data. Further, it was anticipated that the runoff coefficients in WINSLAMM are generally reasonable, given their determination through extensive field monitoring, calibration, and verification (Pitt 2008). However, infiltration measurements within the swale were noted to be highly variable, from 1.00 to 3.61 in/hr for the lower swale, providing substantial error to that parameter and making it the most likely to need calibration, Table A.2.

The measured dynamic infiltration rates were multiplied by a range of factors from 0.5 to 1.2. The model was run with each adjusted infiltration rate, and the Nash-Sutcliffe model efficiency coefficient (NSE) was generated for each model iteration. NSE values and modeled infiltration rates were plotted in Figure 3.17. The figure shows that the NSE reaches a maximum when the measured dynamic infiltration rate is multiplied by 0.80. The calibrated infiltration rates fall within the range of sandy loam and loamy sand per the WinSLAMM manual, Figure A.1. Given that the soils surrounding the site are made up of loam and silt loam, the native soils do not correspond with the calibrated infiltration rate. It is possible that the dense stand of grass provided improved permeability over time due to root action, that fill soils were used for the roadway, and/or that an organic layer developed over time and provided additional water storage. Regardless it is apparent that infiltration tests should be performed instead of assuming infiltration rates in highway medians will correspond with native soils. This is particularly important in light of how sensitive this variable was shown to be during calibration.

Figure 3.18 shows the measured vs. modeled runoff volumes for the final calibrated model. The measured runoff volume for each rain event during the study period was totaled and every modeled runoff volume was totaled; the percent difference was calculated to be 28.4% over the entire study. Percent differences for other catchments modeled by WinSLAMM have ranged from 0 to 27%, with the site size ranging from 4 to 964 acres of varying land use (Paschke et al. 2017). The max NSE was approximately 0.460 which is relatively good considering that only one calibration parameter was utilized, and the rest of the model values were set to suggested values. WinSLAMM appears to be a viable model for highway managers to test the performance of swales, but further study from other locations is needed to verify the results herein. Further, although many parameters within the model can be set to suggested values, using native soil type to estimate infiltration rate does not appear appropriate. On-site infiltration rate testing is

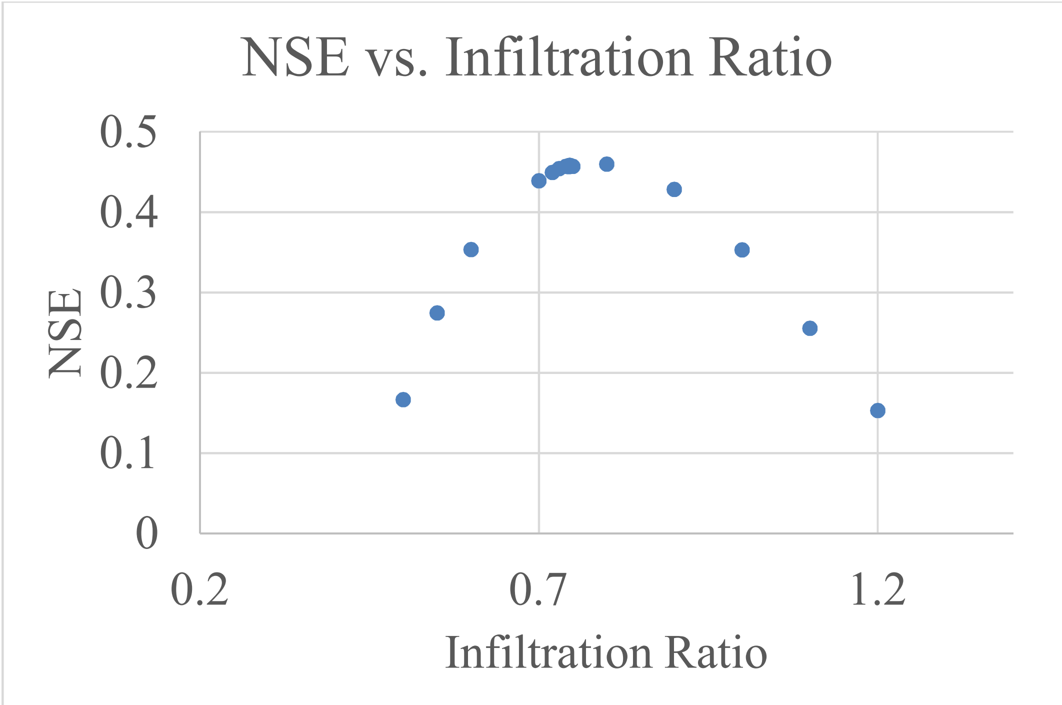

Figure 3.17: NSE Curve

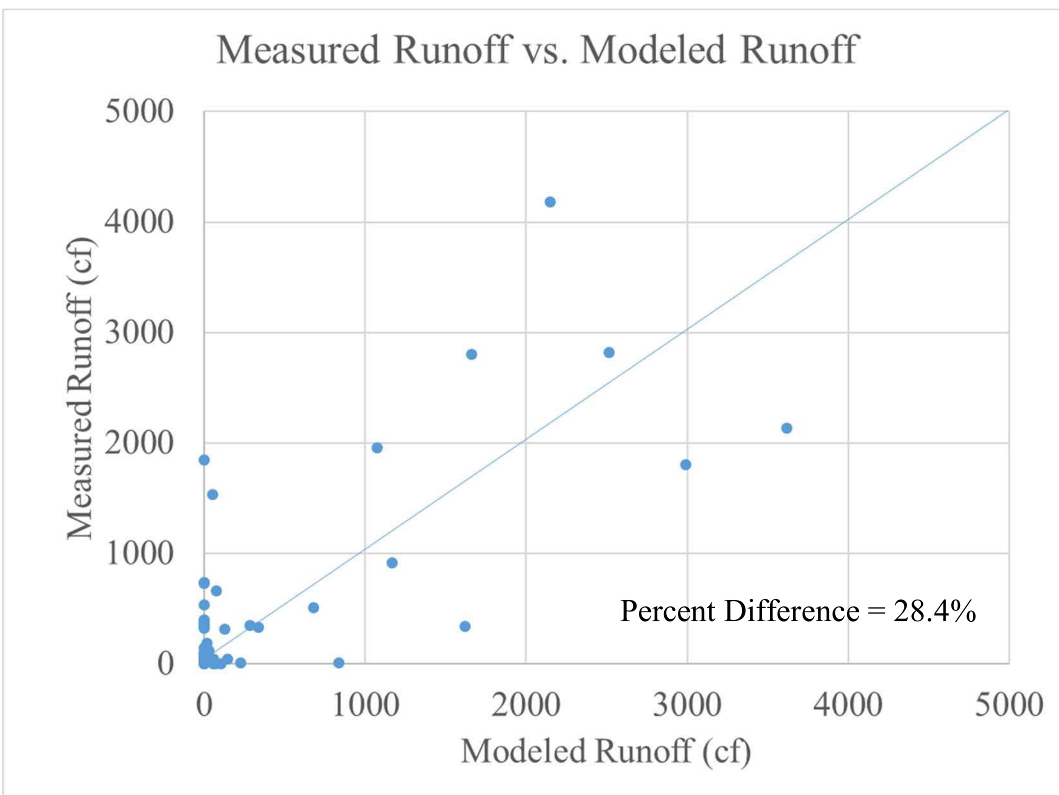

Figure 3.18 Measured vs. Calibrated Model Runoff Volume

important to establish actual infiltration rates. As suggested by Ahmed et al. (2015), this may require a large number of infiltration tests (between 10- 40 per swale, depending on desired uncertainty factor) to be performed for a given location, likely exceeding the number of tests performed herein.

Conclusion

The study investigated the potential for highway grassed wales to contribute to the stormwater management goals of entities such as TDOT to meet MS4 requirements. The results were favorable for volume control, and somewhat mixed for water quality. The swale reduced runoff volume by a median 88.2%, with volume reductions for storms under 0.5 inches ranging from 75.7% to 100%. One explanation for the high reduction percentage is the elevated infiltration rates measured for the site. Despite soil maps of the area identifying soils as primarily loam and silt loam, on-site infiltration tests showed relatively high infiltration rates (1.35 in/hr to 2.15 in/hr). This parameter became critical in modeling the system, showing high sensitivity during the calibration process. The final, calibrated WinSLAMM model showed a percent difference of 28.4% between observed and modeled for the entire study period with an NSE of 0.460. The modeling process reiterated the importance of collecting localized infiltration data when modeling these systems, and confirmed the findings of other studies (Ahmed et al. 2015) that infiltration rates can be highly variable in highway environments. Also, these results suggest the value of WinSLAMM for estimating the performance of highway green space for stormwater management.

TSS reduction performed on the upper end of the 29.7 to 99% range in literature at 88.6% (Allen et al. 2015; Barrett et al. 1998a; Barrett et al. 1998b; Backstrom 2003; Deletic and Fletcher 2006; Kaighn and Yu 1996; Knight et al. 2013; Stage et al. 2012; Yousef et al. 1985; Yu et al. 2001); however, nutrient, chloride, and heavy metal reductions varied. The measured inlet concentration for each nutrient, chloride, and heavy metal was lower than literature values. Consequently, each of the measured outlet values were well below literature reported values, except for lead which was on the lower limit of the range.

Although the swale exported pollutants, the effluent quality was very good with lower concentrations than literature effluent values.

Although there are a number of studies examining the performance of swales as stormwater management features, further study is needed to allow them to be properly credited by regulators. In particular, there is a need to better understand how infiltration rates vary in the highway environment. Examining additional sites to see if infiltration rates are more elevated than the native soil texture class suggests would be beneficial for scaling estimates of highway swale performance from the local to regional level. Also, WinSLAMM was shown to be an effective tool for modeling swale performance, but further study is needed to determine if the observed performance can be replicated in other sites. Using this tool, highway stormwater managers may also be able to determine how swale performance would vary given a range of infiltration rates, catchment sizes, and swale geometries.

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APPENDIX

Table A.1: Measured Detection Limits for IC and ICP-AES Analysis

	Cl (μg/L)	NO2 (μg/L)	NO3 (μg/L)	SO4 (μg/L)	HPO4 (μg/L)	NH4+ (μg/L)	Cu (μg/L)	Zn (μg/L)	Pb (μg/L)
MDL	4.2	5.5	27.3	46.8	120.8	21.4	0.55	15.8	3.2

Table A.2: Measured Infiltration Rates

Upper Right	Upper Middle	Upper Left
9/7/2017	9/7/2017	9/7/2017
5.75	1.23	2.04
6.36	1.27	1.93
5.00	1.19	2.05
5.70	**1.23**	**2.01**
Upper Right	Upper Middle	Upper Left
9/10/2017	9/10/2017	9/10/2017
4.82	1.65	1.83
5.63	1.36	2.08
4.69	1.39	2.50
5.04	**1.47**	**2.14**
Lower Right	Lower Middle	Lower Left
9/7/2017	9/7/2017	9/7/2017
3.67	1.02	0.75
3.49	1.25	0.47
3.41	1.00	0.38
3.52	**1.09**	**0.53**
Lower Right	Lower Middle	Lower Left
9/10/2017	9/10/2017	9/10/2017
4.46	2.80	2.32
3.97	3.23	2.46
4.80	3.61	2.40
4.41	**3.21**	**2.39**

*Each value is in inches per hour and bold values are averages.

Table A.3: Hydrology Results

Rain Event	**Date**	**Rain Total (in)**	**Rain Total (ft)**	**Rain Volume (cf)**	**Runoff Volume (cf)**	**Volume Reduced (cf)**	**Runoff Reduction (%)**
3	11/28/2016	0.93	0.078	5244.3	41	5203	99.2
5	12/4/2016	1.74	0.145	9913.81	1843	8070	81.4
6	12/5/2016	2.19	0.183	12508	4180	8328	66.6

Table A.3: Hydrology Results (continued)

Rain Event	Date	Rain Total (in)	Rain Total (ft)	Rain Volume (cf)	Runoff Volume (cf)	Volume Reduced (cf)	Runoff Reduction (%)
10	12/12/2016	1.57	0.131	8933.79	1804	7130	79.8
11	12/17/2016	0.22	0.018	1151.27	17	1135	98.6
12	12/17/2016	1.8	0.150	10259.7	2800	7460	72.7
13	12/24/2016	0.8	0.067	4494.87	402	4093	91.1
14	12/27/2016	0.55	0.046	3053.67	317	2737	89.6
15	12/28/2016	1.46	0.122	8299.66	2134	6166	74.3
16	1/1/2017	0.9	0.075	5071.36	730	4342	85.6
17	1/3/2017	0.4	0.033	2188.94	395	1794	82.0
18	1/10/2017	0.51	0.043	2823.07	533	2290	81.1
19	1/14/2017	0.13	0.011	632.44	89	543	85.9
23	2/8/2017	0.21	0.018	1093.63	145	948	86.7
24	2/15/2017	0.35	0.029	1900.7	190	1711	90.0
25	2/22/2017	0.11	0.009	517.143	61	456	88.2
26	2/25/2017	0.31	0.026	1670.11	124	1546	92.6
27	2/28/2017	0.54	0.045	2996.02	329	2667	89.0
28	3/1/2017	0.76	0.063	4264.28	1956	2308	54.1
29	3/7/2017	0.51	0.043	2823.07	343	2481	87.9
30	3/10/2017	0.54	0.045	2996.02	511	2485	82.9
31	3/13/2017	0.57	0.048	3168.96	660	2509	79.2
32	3/17/2017	0.63	0.053	3514.85	739	2776	79.0
33	3/21/2017	0.46	0.038	2534.83	347	2188	86.3
35	3/30/2017	0.44	0.037	2419.54	369	2051	84.8
36	4/3/2017	1.35	0.113	7665.53	2822	4843	63.2
38	4/5/2017	0.71	0.059	3976.04	1535	2441	61.4
39	4/17/2017	0.39	0.033	2131.29	42	2090	98.0
40	4/18/2017	0.17	0.014	863.033	49	814	94.4
42	4/27/2017	0.31	0.026	1670.11	99	1571	94.1
43	5/1/2017	0.15	0.013	747.736	6.2	741	99.2
44	5/4/2017	0.58	0.048	3226.61	105	3122	96.8
45	5/5/2017	0.14	0.012	690.088	35	656	95.0
46	5/6/2017	0.19	0.016	978.329	32	947	96.7
47	5/12/2017	0.14	0.012	690.088	1.6	688	99.8
48	5/12/2017	0.45	0.038	2477.18	1.6	2476	99.9

Table A.3: Hydrology Results (continued)

Rain Event	Date	Rain Total (in)	Rain Total (ft)	Rain Volume (cf)	Runoff Volume (cf)	Volume Reduced (cf)	Runoff Reduction (%)
49	5/21/2017	0.3	0.025	1612.46	0.6	1612	100.0
50	5/23/2017	0.2	0.017	1035.98	1.6	1034	99.8
51	5/24/2017	0.56	0.047	3111.31	47	3064	98.5
52	5/27/2017	0.8	0.067	4494.87	344	4151	92.3
53	5/30/2017	0.3	0.025	1612.46	4.1	1608	99.7
60	7/3/2017	0.38	0.032	2073.65	6.8	2067	99.7
61	7/4/2017	0.55	0.046	3053.67	351	2702	88.5
62	7/5/2017	0.57	0.048	3168.96	920	2249	71.0
63	7/6/2017	0.25	0.021	1324.22	321	1003	75.7
64	7/13/2017	0.29	0.024	1554.81	8.6	1546	99.4

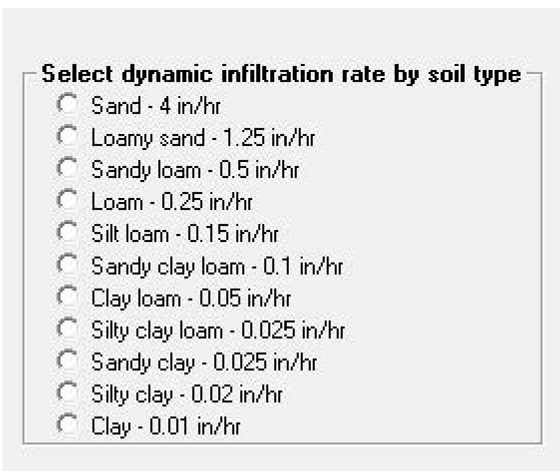

Figure A.1: WinSLAMM Infiltration Values

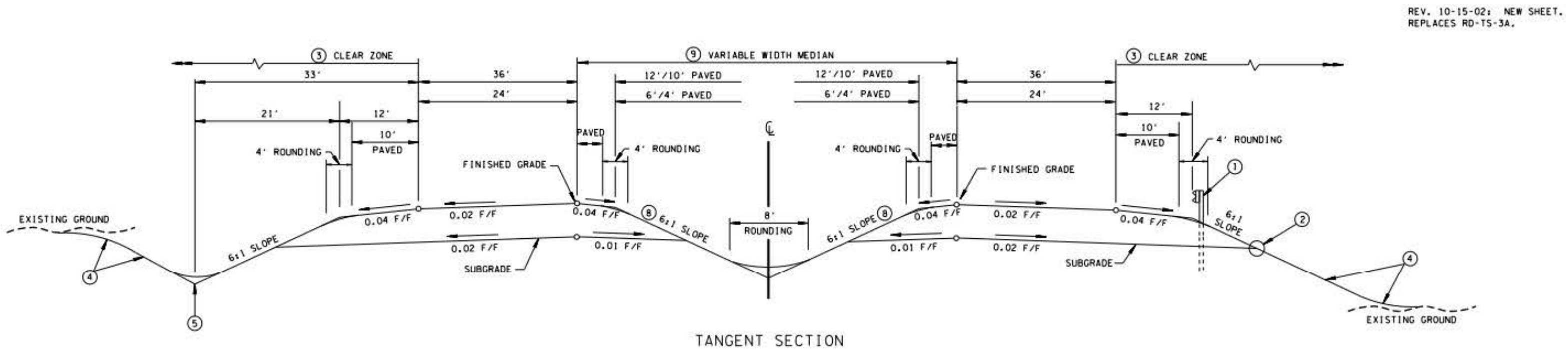

Figure A.2: Typical cross-section of 4 lane arterial highway with depressed medians (TDOT, 2017)

VITA

Bailee Young was born in Knoxville, TN. She went to Farragut High School. After graduation, she studied at the University of Tennessee – Knoxville, where she graduated Summa Cum Laude with a Bachelor of Science in Civil and Environmental Engineering in May 2016. She continued her education at the University of Tennessee – Knoxville, as a graduate research assistant under the direction of Dr. Jon Hathaway, and she will receive her Masters of Science in Environmental Engineering with a concentration in Water Resources in December of 2017.